Strategy for Luminosity Optimization

S. M. White, CERN, Geneva, Switzerland

Abstract

Integrated luminosity is a key parameter for the performance of a particle collider and depends both on beam parameters and operational efficiency. The experimental detectors are turned on and start acquiring useful data only when the machine is declared as stable, it is therefore important to minimize the duration of the activities from the collapsing of the separation bumps until STABLE BEAM is declared. After a review of the current procedure and tools used to bring beams into collision and optimize luminosity, observations and lessons learnt during the 2010 proton run will be presented. The reproducibility and implication of the current procedure regarding machine protection and operation efficiency will be discussed based on this first experience.

INTRODUCTION

The event rate $\dot{N}$ of a process of cross section σ and the instantaneous luminosity $\mathcal{L}_0$ are related for head-on collisions of Gaussian shaped beams by:

$$\mathcal{L}_0 = \frac{N_1 N_2 \, f \, N_b}{2\pi\sqrt{(\sigma_{1x}^2+\sigma_{2x}^2)(\sigma_{1y}^2+\sigma_{2y}^2)}} = \frac{\dot{N}}{\sigma}, \qquad (1)$$

where N_1 and N_2 are the bunch intensities, f the revolution frequency, N_b the number of bunches per beam and $\sigma_{ix,iy}$ the effective transverse beam sizes. The two counter rotating beams do not always collide head-on and the beams can be separated in the horizontal and vertical directions by arbitrary amounts δx and δy. The luminosity is then expressed as:

$$\mathcal{L} = \mathcal{L}_0 \, \exp\left[-\frac{\delta x^2}{2\,(\sigma_{1x}^2+\sigma_{2x}^2)} - \frac{\delta y^2}{2\,(\sigma_{1y}^2+\sigma_{2y}^2)}\right]. \qquad (2)$$

A fit of the measured interaction rates as function of the separation will allow to determine the optimal beam positions to maximize the collision rate. This method was used at the LHC to optimize the luminosity at the four interaction points [1]. As seen in Equation 2 separation scans can also be used to measure the effective beam sizes at the interaction points and therefore normalize the luminosity [2].

AUTOMATED OPTIMIZATION ALGORITHM

A control software was developed for the purpose of luminosity calibration and optimization using separation scans to allow for fast and automated optimization of the four LHC interaction points. Luminosity optimization is usually performed at the beginning of fills when the luminosity lifetime is the worst. The key parameter to develop a routine for luminosity optimization is therefore the efficiency. A simple routine was developed for this purpose which algorithm can be described as follows:

- **1**: take a reference at current location. Integrate the luminosity over n seconds.
- **2**: compute average and rms at this point.
- **3**: move beam1, beam2 or both by d.
- **4**: integrate over n and compute average and rms.
- **5**: compare the two points.
- **6**: step by d if the new point is larger than the reference or by -2d if it is smaller.
- **7**: repeat steps 3 to 5 until the new acquisition is smaller than the previous one displacing the beams in the direction set in step 6.
- **8**: compute a parabola (analytically) from the last three points and find the optimum settings.
- **9**: move to the optimum and take a last acquisition to confirm the increase with respect to the reference.

The user inputs for this routine are n which corresponds to the integration time per step and d which corresponds to the step size. d should be large enough to ensure a significant change in rates between two consecutive acquisitions. The operator can also specify the IP beam and plane that requires an optimization and which signal (detector) should be used. This method, developed at RHIC [3], allows for fast optimization with simple input parameters of a single interaction point or several in parallel or in series.

COMMISSIONING

Figure 1 shows the optimization of all IPs in series during a squeezed optics proton physics fill with a luminosity of about $5\,10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The luminosity was significantly increased in all IPs except for IP1 where no correction was needed. Each scan consisted of 3 steps of 30 s with a range of $\pm 2\sigma$ for a total duration of a few minutes. The overall duration of the full procedure was about 45 minutes.

At low luminosity, the duration of a scan is constrained by the requirements on the statistical accuracy for each scan step. After each fill the optimum settings are saved and

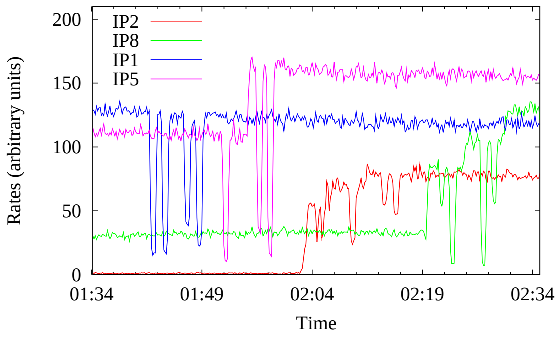

Figure 1: Optimization scans performed in series for squeezed optics in all IPs. The BRAN data shown here are not calibrated which explains the differences between the IPs.

used as the new reference for the next fill. Later on, the algorithm for automated parallel optimization was commissioned and reduced the duration of the optimization to a few minutes. This is shown in Figure 2 in the case of an ion physics fill where only three IPs were optimized as LHCb is not taking data during ions physics.

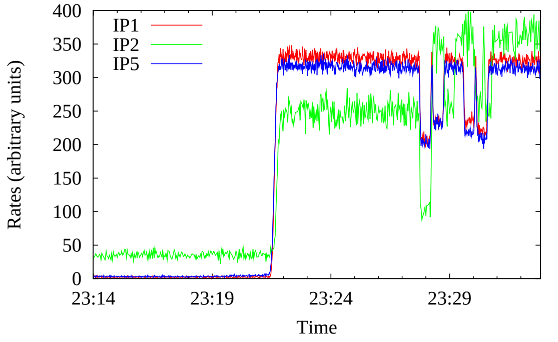

Figure 2: Parallel optimization during an ion physics fill. It took 10 minutes from collision to physics conditions out of which 3 minutes were used to optimize the collision point.

REPRODUCIBILITY AND STABILITY

The luminosity is generally optimized at the beginning of physics fills using dedicated closed orbit bumps. Looking at the variations of the amplitude of these bumps from fill to fill one can estimate the reproducibility of the optimal collision point. This is illustrated in Figure 3 where the fill to fill variations are shown for the last two month of the LHC 2010 proton run. It is seen that the amplitude of the corrections are in most of the case smaller than 60 μm which corresponds to about one beam σ at the IP for an energy of 3.5 TeV and a β^* of 3.5 m. Excluding IP2, the peak and rms corrections are 180 μm and 41 μm in the horizontal plane and 90 μm and 21 μm in the vertical plane. This is clearly sufficient to find the collision point as soon as the injection bumps are ramped down in the case of the 2010 beam parameters. The nominal LHC (7 TeV, β^*=0.55 m) IP beam size is of the order of 17 μm. It could therefore become necessary to improve the reproducibility as the IP beam size becomes smaller.

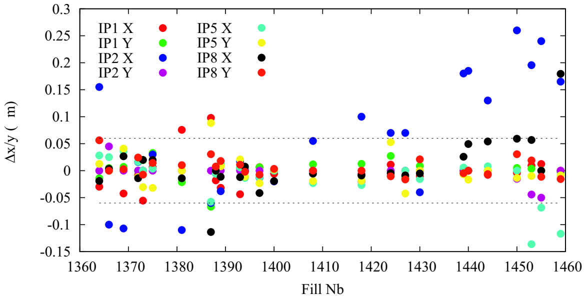

Figure 3: Amplitude of the corrections applied from fill to fill to bring the beams colliding head-on. The fill to fill reproducibility is of the order of 60 μm. Large fluctuations in the horizontal plane at IP2 are observed due to offset collisions.

The large fluctuations observed in the horizontal plane at IP2 are due to operation with offset collisions to reduce the luminosity to the level requested by ALICE. The corrections for IP2 only are shown in Figure 4, one can see on this plot that the vertical plane was in most of the cases not optimized. While some fluctuations are expected when setting the luminosity to a constant value at the beginning of fills when the emittance and intensity vary any offset in the opposite plane (in this case vertical) will also be compensated in the process and will represent an additional source of non-reproducibility. It is therefore desirable to systematically optimize the vertical plane before leveling the luminosity with a separation in the horizontal plane in order to keep the orbit as stable as possible.

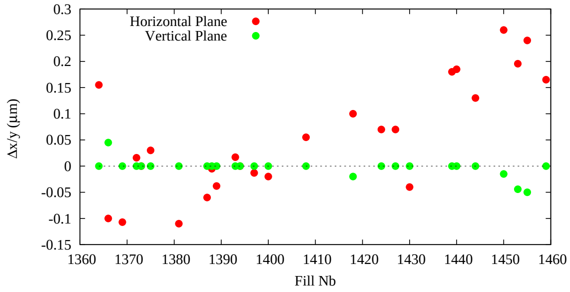

Figure 4: Corrections for IP2 only. Most of the time no corrections were applied in the vertical plane which could have helped reducing the fill to fill variations.

In order to assess the performance in terms of orbit stability during a fill a few scans were performed at the end of fills which results are shown in Table 1. No significant separation drift was observed over the duration of these physics fills which proves the excellent performance of the LHC in terms of stability. It is however important to assess the stability of the collision point in a more systematic way to determine how often these optimization scans would be needed. This could be done almost parasitically during physics fills by regularly performing optimization scans in order to derive some systematic behavior.

Table 1: Position of the peak luminosity as measured with end of fills scans.

	IP1		IP5	
Fill Nb	Δx (μm)	Δy (μm)	Δx (μm)	Δy (μm)
1366	3	3	2	10
1372	1	-4	7	-2
1373	6	16	-5	-3
1393	-5	-2	-2	-5
1450	-1	4	-	-

COLLAPSING THE SEPARATION BUMPS

The beams are brought into collision through a 'PHYSICS' beam process that ramps down the injection separation bumps and loads the optimized bump settings from the last physics fill. The overall duration of this operation was 108 seconds for protons in 2010. After that, global corrections are performed and the luminosity is optimized at the four interaction points with scans before STABLE BEAM is declared. As illustrated in Figure 2, from the moment when the injection bumps are ramped down it takes about 10 minutes to declare STABLE BEAM. During this time no physics data are acquired by the experiments as they can fully turn on their detectors only after STABLE BEAM is declared. It is therefore relevant to investigate possibilities to improve efficiency in order declare STABLE BEAM as soon as possible.

Injection separation bumps are generated with orbit correctors. In order to collapse the separation bumps the fraction of the field of these correctors used to separate the beams has to be ramped down to zero. In this process a parabolic-linear-parabolic ramp will be assumed. The parabolic phases depend on an acceleration term and the linear phase on dI/dt. The separation at the IP varies linearly with the current applied to the correctors. It is possible to find the minimum collapsing time by varying the strength of the MCBX.

Figure 5 shows the evolution of the collapsing time versus the MCBX angular kick at IP1 for the 3.5 TeV LHC optics (full 2 mm separation). Given the actual hardware settings, the limitation comes from the MCBX and the collapsing time only depends on its acceleration and ramping rate. About 20 seconds can be gained with the current hardware performance, increasing the ramp rate of the MCBX to 5 A/s (as initially foreseen) or splitting the strength between the different MCBXs would significantly reduce the overall duration. The collapsing time scales with energy as the required current in the orbit correctors will increase, in this case the gain becomes more significant as demonstrated in [4]. In 2010, the bumps were collapsed from the full 2 mm separation required at injection. As the beams are ramped to high energy the beam size at the IP is reduced and therefore the IP separation could also be reduced in this process in order to gain some time in the process of bringing them into collision.

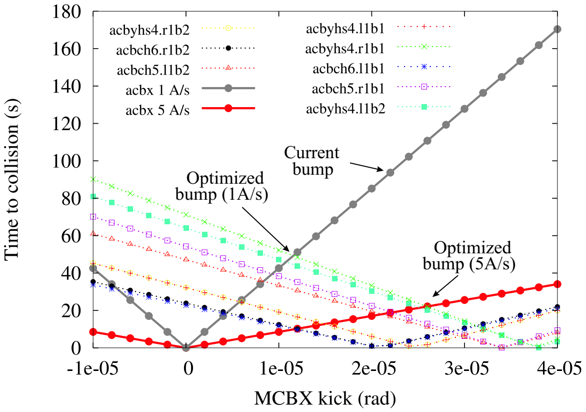

Figure 5: Time required to bring beams into collision as a function of the MCBX strength for IP1. About 20 seconds can be gained with the current hardware performance, changing the ramp rate of the MCBX to 5 A/s would reduce this time to about 20 seconds.

LUMINOSITY OPTIMIZATION AND MACHINE PROTECTION

The beams are displaced at the IP via a closed orbit bump that consists of four magnets and allows to control the beams independently.

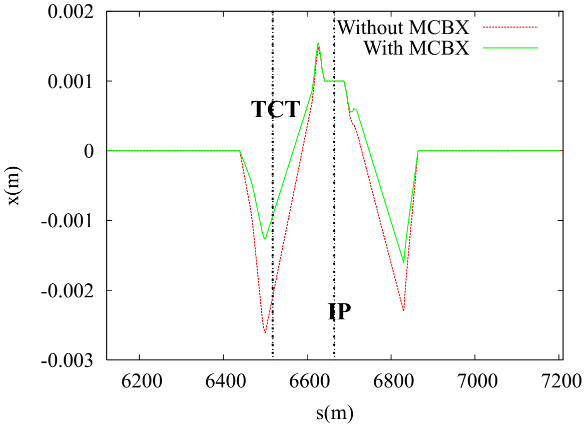

Figure 6: Example of closed orbit bumps using different orbit correctors at IP5. Displacing the beam at the IP also changes the orbit at the tertiary collimator location.

One can see in Figure 6 that a four magnet separation bump extends over a large fraction of the straight section around the IP. More specifically, displacing the beams at the IP will result in a change of orbit at the tertiary collimators (TCT). Given the non-negligible offset at the TCT introduced by the bumps, one has to ensure that while performing a separation scan the beams remain far enough from the aperture set by the collimators and that the displacement does not compromise the machine protection. In 2010, the displacement at the TCT was minimized by splitting the amplitude of the corrections required to find the optimum collision point between the two beams. Initial estimates [5] showed that in case the orbit is stable within tolerance and does not drift to far off the reference orbit, there should be sufficient margins to perform optimization scans with limited separation range while preserving the collimator hierarchy and the triplet protection. It is however important to confirm these estimates with experimental data.

A detailed study of the collimation system performance and estimates of the real available margins based on measurements for the 2010 proton run can be found in [6] and [7]. The margin was estimated to be of the order of 2.5 σ for the 3.5 m optics. On the two top plots of Figure 7 the orbit fluctuations at the TCTs expected from the scans (estimated from the bump amplitude) are shown. The two bottom plots show the measured orbit fluctuations from fill to fill. The estimated fluctuations from the scans are in general smaller than 0.2 σ and go up to 0.5 σ in the case of IP2 where the beams were colliding with an offset. This is well within the margin of 2.5 σ estimated in [7]. The measured orbit fluctuations are larger than what is expected from the scans only, and large offsets (up to 1.5 σ) are observed from the beginning. One can conclude from these observations that during the 2010 proton the optimization scans amplitude remained well within the safety margins and only contributed partially to the overall orbit fluctuations in the TCT region. A review of the procedure to control and correct the orbit in the IR regions could improve these performance and the stability of the collision point.

A possible scenario for the 2011 LHC proton run is to operate with a higher energy and a β^* of 1.5 m in which case the margin was estimated to 1.5 σ [7]. It is possible to estimate the contributions to the orbit fluctuations at the TCTs from scans by rescaling the 2010 measurements. This is shown in Figure 8 where an energy of 4 TeV was considered. In case the energy remains at 3.5 TeV this picture will improve as the beam size at the TCTs will be larger. It is seen that the maximum displacement is of the order of 0.2 σ for an rms of 0.05 σ which is well within the available margin, it should therefore be possible to safely operate the machine using the same procedure as in 2010 for luminosity optimization assuming the overall performance of the machine are the same. As β^* is decreased the aperture in the triplets becomes tighter. One should therefore make sure the triplets remain in the shadow of the TCTs when driving IP separation bumps to large amplitudes.

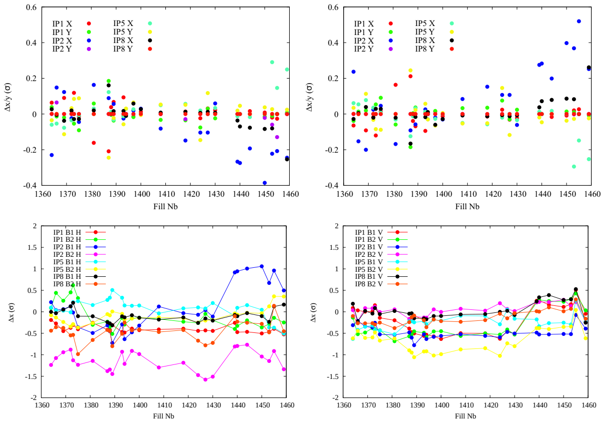

Figure 7: The two top plots illustrate the displacement at the TCT resulting from the optimization scans for beam 1 (left) and beam 2 (right). One can observe a symmetry between the two beams as the corrections amplitude is split in between them. The fluctuations are of the order of 0.2 σ. The two bottom plots show the difference with respect to the reference orbit at the TCT as measured from the BPMs in the horizontal (left) and vertical (right) planes. One can see that the fill to fill fluctuations are larger than what is expected from the scans.

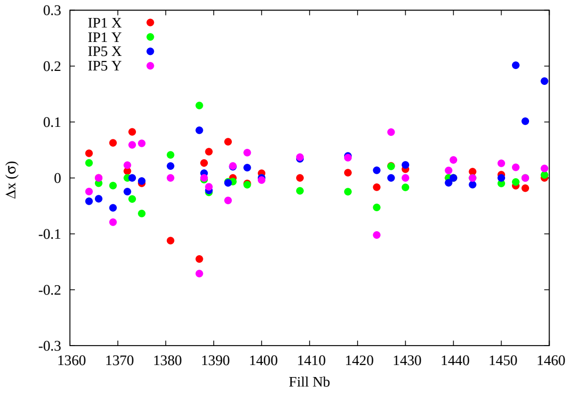

Figure 8: Rescaling of the observed displacement at the TCT from the scans at 3.5 TeV and β^*=3.5 m to 4 TeV and β^*=1.5 m. The expected fluctuations are of the order of 0.1 σ.

CONCLUSION

The procedures and tools for luminosity optimization were successfully commissioned and operated during the 2010 LHC run. The performance are excellent for a first year of operation. The fill to fill reproducibility could be further improved with a better control of the orbit in the IR region which could become necessary when the IP beam size is significantly reduced. No significant drift was observed during a fill. The interaction with the machine protection system proved to be small in 2010 and no significant issues are foreseen in the case of smaller β^* and higher energy as long as the performance in terms of reproducibility and stability remain the same. The bump amplitudes should however be carefully monitored in order to ensure that the orbit at the TCTs and at the triplets remains within the margins set by the collimation system. The procedure to bring beams into collision is well optimized. The efficiency could be slightly improved with an optimization of the separation bumps and a reduction of the separation during the ramp. The orbit fluctuations at the TCTs during optimization scans observed in 2010 as well as the estimates for 2011 are well within the available margins, performing these scans during STABLE BEAM could therefore be considered as a possible improvement of the procedure.

REFERENCES

[1] S. M. White, R. Alemany-Fernandez, H. Burkhardt, M. Lamont, ”First Luminosity Scans in the LHC”, IPAC Proceedings, 2010.

[2] S. Van Der Meer, ISR-PO/68-31, KEK68-64.

[3] A. Drees, T. D’Ottavio, ”Luminosity Optimization Using Automated IR Steering at RHIC”, EPAC Proceedings, 2004.

[4] S. M. White, H. Burkhardt, S. Fartoukh, T. Pieloni, ”Optimization of the LHC Separation Bumps Including Beam-Beam Effects”, PAC Proceedings, 2009.

[5] S. M. White, H. Burkhardt, ”Luminosity Optimization”, Evian Proceedings, 2010.

[6] D. Wollmann, ”Multi-turn losses and cleaning”, this workshop.

[7] R. Bruce, ”How low can we go? Getting below 3.5 m β^*, this workshop.